The optical flare and afterglow light curve of GRB 050904 at redshift z=6.29

D. M. Wei[1,2], T. Yan[1,2], and Y. Z. Fan[1,2]

[1] *Purple Mountain Observatory, Chinese Academy of Science, Nanjing 210008, China.*
[2] *National Astronomical Observatories,Chinese Academy of Sciences, Beijing, 100012, China.*

ABSTRACT

GRB050904 is very interesting since it is by far the most distant GRB event known to date ($z = 6.29$). It was reported that during the prompt high energy emission phase, a very bright optical flare was detected, and it was temporal coincident with an X-ray flare. Here we use two models to explain the optical flare, One is the "late internal shock model", in which the optical flare is produced by the synchrotron radiation of the electrons accelerated by the late internal shock, and the X-ray flare is produced by the synchrotron-self-Compton mechanism. The other is the external forward-reverse shock model, in which the optical flare is from the reverse shock emission and the X-ray flare is attributed to the central engine activity. We show that with proper parameters, a bright optical flare can appear in both models. We think the "late internal shock model" is more favored since in this model the optical flash and the X-ray flare have the same origin, which provides a natural explanation of the temporal coincidence of them. In the forward-reverse shock scenario, fits to the optical flare and the late afterglow suggests that the physical parameters of the reverse shock are much different from that of forward shock, as found in modeling the optical flash of GRB 990123 previously.

Subject headings: Gamma Rays: bursts−ISM: jets and outflows–radiation mechanisms: nonthermal

1. Introduction

Gamma-Ray Bursts (GRBs) are bright flashes of high energy photons usually lasting about several seconds. They are by far the most luminous objects in the universe, they emit so large amounts of energy (up to 10^{53} ergs) and thus can be detected up to very high redshifts ($z > 5$).

GRB050904 was detected by the Burst Alert Telescope (BAT) onboard Swift on 2005 September 4 at 01:51:44 UT (Cummings et al. 2005). It was a long (≤ 500 seconds duration in BAT), multi-peaked, bight burst, the 15 - 150 keV fluence was $(5.4 \pm 0.2) \times 10^{-6}$ erg cm^{-2}, the spectrum can be described by a power law with a photon index ~ -1.34, its redshift has been measured by several groups (Haislip et al. 2005; Antonelli et al. 2005; Price et al. 2005), $z = 6.29$ makes it to be by far the most distant GRB discovered to date.

Boër et al. (2005) reported that they detected a very bright optical flare during the prompt high energy emission phase, and at the same time there is an X-ray flare. It is widely believed that the reverse shock synchrotron radiation usually peaks in the optical/IR band, and this emission has been successful in interpreting the early optical emission from GRB990123 (Akerlof et al. 1999; Sari & Piran 1999; Wang et al. 2000; Fan et al. 2002; Zhang et al. 2003; Nakar & Piran 2005), GRB021211 (Fox et al. 2003; Li et al. 2003; Wei 2003; Kumar & Panaitescu 2003), GRB041219a (Blake et al. 2005; Fan et al. 2005b) and GRB 050525a (Blustin et al. 2005; Shao & Dai 2005). However in this reverse shock model, it is expected that the emission has a negligible contribution in the X-ray band (However, see Fan & Wei 2005). Strong optical flare accompanying an X-ray flare may also be accounted for by the "late internal shock model" (Fan & Wei 2005). Originally, that model has been proposed to interpret the X-ray flare detected in GRB 011121 (Piro et al. 2005) and many XRT X-ray flares (Burrows et al. 2005; Zhang et al. 2005; Nousek et al. 2005).

The optical afterglow light curve of GRB050904 cannot be described by a simple power law, between $\sim$ 3 hours and 0.5 day after the burst, the fading of the afterglow can be described by a power law with index -1.36. However after this time the light curve flattened to a temporal index of -0.82 (Haislip et al. 2005). Tagliaferri et al. (2005) have found a break in the light curve at time $t_b \simeq 2.6$ day, which may be the jet effect. In this Letter, we try to explain the optical flare with two models, i.e. the reverse shock emission and the late internal shock model, and then we will fit the afterglow light curve including energy injection and jet effects.

2. Explanation of the optical flare

2.1. The late internal shock model

In the standard shock scenario, the prompt gamma-ray emission is produced by the internal shock, and the burst duration is determined by the active timescale of the central engine. However, some authors suggest that the activity of the central engine may be much longer than the GRB duration, which can give rise to some signatures in multi-wavelength

afterglows (Dai & Lu 1998; Zhang & Mészáros 2001; Granot et al. 2003; Ioka et al. 2005). Furthermore, it has been proposed that the Fe line observed in some GRB X-ray afterglows are produced by the late time energy injection (Rees & Mészáros 2000; Gao & Wei 2005).

Fan & Wei (2005) first proposed the late internal shock model to account for the bright X-ray flares detected in many GRBs. Here we will show that the late internal shock model not only can produce the X-ray flare, but also can produce the optical flare with proper parameters.

Following Fan & Wei (2005), the typical synchrotron radiation frequency can be estimated by

$$\begin{aligned}\nu_m &\approx 8.5\times 10^{15}(\frac{\epsilon_e}{0.4})^2\epsilon_{B,-2}^{1/2}(\Gamma_{sh}-1)^{5/2}\Gamma_{sh}^{1/2}L_{m,52}^{1/2}\\ &\quad \Gamma_2^{-2}\delta t_1^{-1}\ \mathrm{Hz},\end{aligned}\tag{1}$$

where L_m is the outflow luminosity, Γ_{sh} is the Lorentz factor of the internal shock, Γ is the Lorentz factor of the emitting shell, δt is the observed typical variability timescale, ϵ_B and ϵ_e are the energy fractions occupied by the magnetic field and electrons, respectively. Here the convention $Q_x = Q/10^x$ has been adopted in cgs units throughout the text.

The cooling Lorentz factor is $\gamma_{e,c} \simeq 7.7\times 10^8(1+z)/[(1+Y)\Gamma B^2\delta t]$, where $Y = [-1+\sqrt{1+4x\epsilon_e/\epsilon_B}]/2$ is the Compton parameter, $x \simeq \min\{1, (\nu_m/\nu_c)^{(p-2)/2}\}$ (Sari & Esin 2001). Then the cooling frequency is

$$\begin{aligned}\nu_c &\approx 1.6\times 10^{11}(\frac{1+z}{7.29})^{-2}\epsilon_B^{-3/2}[\Gamma_{sh}(\Gamma_{sh}-1)]^{-3/2}L_{m,52}^{-3/2}\\ &\quad \Gamma_2^{8}\delta t_1(1+Y)^{-2}\ \mathrm{Hz}\end{aligned}\tag{2}$$

The synchrotron-self-absorption frequency is about (Li & Song 2004; Fan & Wei 2005)

$$\begin{aligned}\nu_a &\approx 2.9\times 10^{14}(\frac{1+z}{7.29})^{-2/7}\epsilon_{B,-2}^{1/14}[\Gamma_{sh}(\Gamma_{sh}-1)]^{1/14}L_{m,52}^{1/14}\\ &\quad L_{syn,50}^{2/7}\Gamma_2^{-8/7}\delta t_1^{-5/7}\ \mathrm{Hz}\end{aligned}\tag{3}$$

where L_{syn} is the synchrotron radiation luminosity. The maximum flux of synchrotron radiation is $F_{max} \approx 3\sqrt{3}\Phi_p(1+z)N_e m_e c^2\sigma_T\Gamma B/(32\pi^2 q_e D_L^2)$, where q_e is the charge of electron, $N_e = L_m\delta t/[(1+z)\Gamma m_p c^2$ is the total number of emitting electrons, Φ_P is a function of

p, for $p = 2.5$, $\Phi_P \simeq 0.6$ (Wijers & Galama 1999). D_L is the luminosity distance, we adopt $(\Omega_M, \Omega_\Lambda, h) = (0.3, 0.7, 0.71)$. Then for the case $\nu_c < \nu_a < \nu_{obs} < \nu_m$, the observed flux at frequency ν_{obs} should be

$$\begin{aligned} F_\nu &\approx 100(\frac{\nu_{obs}}{3 \times 10^{14}\mathrm{Hz}})^{-1/2} L_{m,52}^{3/4} \Gamma_2 \epsilon_{B,-2}^{-1/4} [\Gamma_{sh}(\Gamma_{sh} - 1)]^{-1/4} \\ & D_{L,29.3}^{-2} \delta t_1^{1/2} (1+Y)^{-1} \text{ mJy} \end{aligned} \tag{4}$$

Now we turn to the observation. Boër et al. (2005) reported that they detected a bright optical flare at frequency $\nu_{obs} = 3 \times 10^{14}$ Hz, the peak flux is 48 mJy. Meanwhile, the Swift XRT data shows that there is also a peak in the X-ray light curve at nearly the same time with the optical flare, which suggests that the optical flare and the X-ray peak may have the same origin. The slope of the X-ray spectrum is about -1/2, and the flux at 1KeV is about 0.08 mJy.

In our late internal shock model, if we take the values as follows: $\epsilon_e = 0.4$, $\epsilon_B = 0.02$, $L_m = 10^{52}$ ergs^{-1}, $\Gamma = 200$, $\Gamma_{sh} = 1.6$, $\delta t = 20s$, then we find $\nu_m \sim 6.3 \times 10^{14}$ Hz, $\nu_a \sim 8.4 \times 10^{13}$ Hz, $\nu_c \sim 1.2 \times 10^{12}$Hz, so it is in the fast cooling phase, between ν_a and ν_m the spectrum takes the form $F_\nu \propto \nu^{-1/2}$, and at the observed frequency (3×10^{14} Hz) the flux is 49 mJy, which is quite consistent with the observation. In addition, with the values of ϵ_e and ϵ_B, the Compton parameter $Y \simeq 4$, then the synchrotron photons will be Compton scattered to high energy, the energy spectrum between 10^{16} Hz and 10^{19} Hz is also $F_\nu \propto \nu^{-1/2}$, and we can estimate the flux at 1KeV to be about 0.06 mJy, which is also consistent with the observation well.

2.2. The reverse shock model

After the internal shock phase, as the fireball is decelerated by the circumburst medium, usually a pair of shocks develop (Mészáros & Rees 1997; Sari & Piran 1999; Kobayashi 2000). The early optical afterglow lightcurve is usually composed of the contributions from both the forward (FS) and the reverse shocks (RS). With that model, the very early optical/IR flash following GRB 990123, GRB 021211, GRB 041219a and GRB 050525a could be well modelled by assuming the physical parameters are quite different for the FS and RS (Fan et al. 2002; Zhang et al. 2003; Kumar & Panaitescu 2003; McMahon et al. 2004; Fan et al. 2005b; Blustin et al. 2005). For example, Fan et al. (2002) performed a detailed fit to the optical flash of GRB 990123 data and obtained $\epsilon_e^{\rm r} = 4.7\epsilon_e^{\rm f} = 0.6$ and $\epsilon_B^{\rm r} = 400\epsilon_B^{\rm f} = 0.4$, where the superscripts "r" and "f" represent RS and FS, respectively.

Böer et al. (2005) found that both the optical flare and the gamma-ray burst of GRB 050904 were as energetic as those of GRB 990123 (in the rest frame of the GRBs). If other parameters (including the initial Lorentz factor of the ejecta, the number density of the interstellar medium n) are similar for these two events, then the resulted shock parameters should be similar, too! So it is very likely that in the current case the shock parameters of FS and RS are also different.

Recently, Yan et al. (2005) have developed a code to calculate the GRB afterglow light curves, including the FS and the RS emission components. In the current calculation, there are two novel effects have been taken into account. One is that in previous works, the Lorentz factor of the outflow as well as the comoving number density of particle are assumed to be constant. This may not be the case since in the standard fireball model, the gamma-ray burst is from the internal shocks. The detected gamma-ray lightcurve is so variable that the involved outflow may be variable, too (both the Lorentz factor and the particle number density). In order to model the optical plateau (Boër et al. 2005) and partly for convenience, in this work we assume the outflow can be approximated as two parts. Their bulk Lorentz factors, isotropic energies and widths are ($\eta_{(1)}$, $E_{iso(1)}$, $\Delta_{(1)}$) and ($\eta_{(2)}$, $E_{iso(2)}$, $\Delta_{(2)}$), respectively. The other is the more reliable calculation of the arriving time of the RS emission. We take the emitting time of the first $\gamma-$ray photon as our zero point of time. On the line of sight ($\theta = 0$), a gamma-ray photon γ_P arriving us at t implies that the distance of corresponding electron (i.e., point P, at which the bulk Lorentz factor is η) to the initial outflow front is $\sim ct/(1+z)$. The radial distance of the FS front to the central engine is R_P when the RS crosses point P. At that time, the width between photon γ_P and point P is $\approx (1-\beta_\eta)R_P$, where $\beta_\eta = \sqrt{1-1/\eta^2}$. Therefore, the arriving time of the RS emission from point P should be $t+(1+z)(1-\beta_\eta)R_p/c$. It is straightforward to extend this calculation to the cases of $\theta \neq 0$. It is found that the $I-$band flare of GRB 050904 can be well reproduced with the following parameters (see the insert of Fig. 1): the isotropic energy of the outflow is $\eta_{(1),2} = 380$, $E_{iso(1),54} = 0.4$, $\Delta_{(1),12} = 1.3$, $\eta_{(2),2} = 800$, $E_{iso(2),54} = 0.3$, $\Delta_{(2),12} = 0.7$, $n = 3\ \mathrm{cm}^{-3}$, $\epsilon_e^{\mathrm{r}} = 0.6$, and $\epsilon_B^{\mathrm{r}} = 0.4$. It is surprising to see that the resulting reverse shock parameters are nearly the same as those of GRB 990123 (Fan et al. 2002).

Can the X-ray flare be from the RS, too? The answer is negative. Firstly, as shown by Fan & Wei (2005), the decline of the X-ray emission of the RS can not be steeper than $t^{-(2+p/2)}$, which is inconsistent with the observation. Secondly, now the reverse shock region is significantly magnetized, so the RS emission in X-ray band should also be dominated by the synchrotron radiation. Thus the X-ray band emission should be an extension of the optical emission. However, the observation shows the optical-to-X-ray bands emission can not be described by a simple synchrotron spectra (Boër et al. 2005). Therefore, the X-ray flare accompanying the optical flare should be attributed to the activity of the central engine

in the RS model.

3. Fits to the late $J-$band afterglow

The multi-wavelength afterglow light curves (especially the $J-$band one) of GRB050904 have been detected (Haislip et al. 2005; Tagliaferri et al. 2005 and the references therein). Between ~ 3 hours and 0.5 day after the burst, the fading of the afterglow can be described by a power law with index -1.36. After that time the light curve flattened to a temporal index of -0.82. A break appears at time $t_b \simeq 2.6$ day, which suggests that the outflow may be a jet. In this Letter we pay more attention to the optical flattening. We note that at the observer time $t \sim 10^4 - 10^5$ s, there are strong X-ray flares (Cusumano et al. 2005; Price et al. 2005; Watson et al. 2005). Fan & Wei (2005) suggested that when the moderate relativistic outflow powering the X-ray flare catched up with the initial GRB ejecta, a flattening would occur in the long-wavelength afterglow light curve. In the calculation, we assume that between $t \sim 4 \times 10^4$ seconds and $t \sim 1.5$ day, significant part of energy has been injected into the decelerating GRB ejecta. Similar to Zhang et al. (2005), the energy injection rate has been taken as $dE_{inj}/[dt/(1+z)] = Ac^2(t/t_0)^{-0.5}$, where A is a constant. We take $A = 0$ when there is no energy injection. With the energy injection, the equation (8) of Huang et al. (2000) should be replaced by

$$d\gamma = \frac{(1-\gamma^2)dm + A(t/t_0)^{-0.5}[dt/(1+z)]}{M_{ej} + \epsilon m + 2(1-\epsilon)\gamma m}, \tag{5}$$

where γ is the bulk Lorentz factor of the GRB ejecta, M_{ej} is the rest mass of the initial GRB ejecta, m is the mass of the medium swept by the GRB ejecta (which is governed by $dm = 4\pi R^2 n m_p dR$, where m_p is the rest mass of proton, $dR = \gamma(\gamma + \sqrt{\gamma^2 - 1})cdt/(1+z)$, $\epsilon = x\epsilon_e$ is the radiation efficiency. With the dynamical evolution of the ejecta, it is straightforward to calculate its FS emission (e.g., Huang et al. 2000; Yan et al. 2005).

The fits to the $J-$band data (taken from Haislip et al. [2005] and Tagliaferri et al. [2005]) are presented in Fig. 1. It is found that the data can be well modeled with the following parameters: $E_{\rm iso,54} = 0.7$, $n = 3\ {\rm cm^{-3}}$, $\epsilon_e^{\rm f} = 0.15$, $\epsilon_B^{\rm f} = 0.001$, $A = 7 \times 10^{49}$ ergs s^{-1}, $t_0 = 4 \times 10^4$ s, and the jet angle $\theta_j = 0.054$. Note that the value of θ_j is obtained from fitting the afterglow light curve, not from the simple analytic relation. Comparing with the reverse shock parameters derived in §2.2, the shock parameters of the FS and the RS are quite different, as that found in GRB 990123 (Fan et al. 2002; see also Zhang et al. 2003). The isotropic energy of the $\gamma-$rays is $\sim 5 \times 10^{53}$ ergs and the derived $\theta_j = 0.054$, so the geometry corrected energy should be $\sim 7 \times 10^{50}$ ergs, which is typical for the GRBs detected

by BeppoSAX, HETE-2 and Swift. In our treatment, the flattening is caused by the late time energy injection. The total isotropic energy injected into the GRB ejecta is $\sim 6 \times 10^{53}$ ergs.

4. Discussion and conclusion

The bright optical flare has been detected in GRB050904, which is as bright as the optical flash of GRB990123 (in the rest frame of bursts) and seems to be accompanied by an X-ray flare (Boër et al. 2005). Here we explored two possible models to account for that observation. One is the "late internal shock model", in which the optical flare is produced by the synchrotron radiation of the electrons accelerated by the late internal shock, and the X-ray flare is produced by the synchrotron-self-Compton process. [1] The other is the external forward-reverse shock model, in which the optical flare is from the reverse shock emission and the X-ray flare is attributed to the central engine activity. We show that with proper parameters, a bright optical flare can appear in both models.

In the forward-reverse shock scenario and with late time energy injection, we have modeled the optical flare as well as the late $J-$band afterglow numerically. The resulted shock parameters of the forward/reverse shocks are $\epsilon_e^{\rm r} = 4\epsilon_e^{\rm f} = 0.6$ and $\epsilon_B^{\rm r} = 400\epsilon_B^{\rm f} = 0.4$, respectively. They are quite similar to those found in GRB 990123 (Panaitescu & Kumar 2001; Fan et al. 2002), which is a natural result in view of the similarity between these two GRBs and their optical flares (in the rest frame of bursts).

As for the reverse shock emission, previous works usually assumed that the physical parameters are uniform, this greatly simplify the calculation. But in reality, the observed gamma-ray emission light curve is much variable, so it is very likely that the involved outflow should be also variable. We notice that if the parameters are uniform, then before the peak time the flux rises quickly, cannot account for the observed plateau (Kobayashi 2000; Boër et al. 2005). Here just for simplicity, we divide the outflow into two parts. We expect that in the realistic case, the outflow should be non-uniform, so the parameters should have a continuous distribution within the shell, but the calculation is complicated.

Although both the "late internal shock model" and the reverse shock emission can account for the observed optical flash and the X-ray flare, We think the "late internal shock

[1] However, in some cases the synchrotron emission may peak in keV energy band, then the IC component would peak at GeV energy band (unless the outflow is highly magnetized, as suggested by Fan, Zhang & Proga (2005a)), which may be detectable for the upcoming GLAST. This possibility will be discussed in great detail elsewhere.

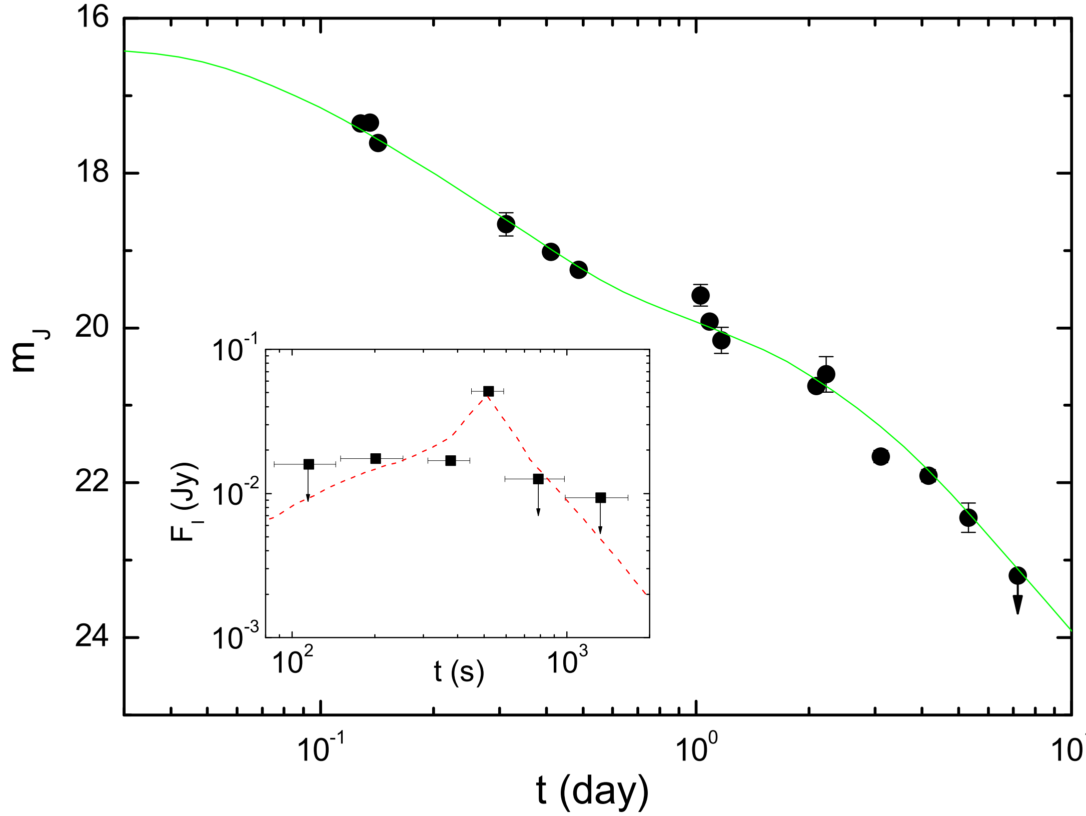

Fig. 1.— Modeling the I-band flare (the insert) and the J-band afterglow of GRB 050904. In the insert, the $I-$band flare data (the filled rectangles) are taken from Boër et al. (2005), the dashed line is the theoretical light curve of the reverse shock emission. The $J-$band afterglow data (the filled circles) are taken from Haislip et al. (2005) and Tagliaferri et al. (2005). The solid line is the theoretical light curve of the $J-$band afterglow.

model" is more favored since in this model the optical flash and the X-ray flare have the same origin, which provides a natural explanation of the temporal coincidence of them. In the late internal shock model, it is needed that after the prompt $\gamma-$ray burst phase, the central engine could re-start. Recently two models have been proposed for the production of late energy injection (King et al. 2005; Perna et al. 2005; MacFadyen et al. 2005 proposed another model to account for the X-ray flare in short GRBs). While in the reverse shock model, the temporal coincidence of the optical flash and the X-ray flare can only be regarded as fortuitous. In addition, we note that in the late internal shock model, the typical synchrotron radiation frequency strongly depends on the parameters, such as Γ, Γ_{sh}, L_m, δt etc., and for different burst sources it is natural that these parameters are different,so we expect that the late internal shock model not only can produce the optical or X-ray flare, but also can produce the flare at other wavelength, such as at the ultraviolet or infrared. Meanwhile we predict that the synchrotron-self-Compton process may produce emission at high energy band ($\sim$ GeV).

Despite its high redshift, the optical afterglow of GRB050904 is not peculiar with respect to other GRBs. Recently Zhang et al. (2005) and Nousek et al. (2005) analyzed the X-ray afterglows of many GRBs, they found some features (the X-ray flares, the flattening of the light curve, a late time break) occurred in a good fraction of GRBs. These features are consistent with the afterglow of GRB050904. We suggest that the progenitor of GRB050904 may be not quite different from that of other GRBs in view of these similarity.

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